Reliability studies of 1kHz KrF Excimer Lasers for DUV Lithography

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ABSTRACT

Chip makers are gearing up for 686-class micro-processors and 64Mb production. These require producing <0.30μm critical features. They are also focusing on 256Mb DRAMs that require below 0.25μm design rules. Therefore, the shift from mercury lamp based i-line to 248nm Deep-Ultra-Violet (DUV) steppers has begun in earnest. Current KrF laser models from several suppliers satisfy the optical requirements necessary for pilot production. However, as the move from DUV lithography R&D environment to production occurs, the laser's manufacturability, uptime requirements and cost-of-operation (CoO) become more demanding. The chip maker requires Reliability, Availability and Maintainability (RAM) data from laser manufacturers to support uptime and CoO estimates. Often, such data are required long before the lasers actually go into production.

The general approach hitherto followed by laser suppliers in determining these numbers was to lifetest one laser for a certain duration and document the failure mechanisms. The cost-of-operation is then estimated from the cost of replacement parts or sub-systems. The sub-systems that make the highest contribution to the cost-of-operation are then addressed (e.g. laser chamber). However, nuisance failures (such as blown fuse, defective valve, software bugs related shutdowns) are rarely addressed although in some cases these failures alone can cause significant downtime during laser manufacture/test and during use by chip makers. Therefore, the CoO data essentially reflect the cost of replacements parts. The RAM data, however, is at best, an educated guess by the laser manufacturer.

In the strict sense, RAM data are measures of equipment performance which have been widely used in industry for several years. Such is not the case for any excimer laser for DUV lithography, where the transition to it's use in a production environment from R&D has just begun. The actual usage data, today, from these lasers are negligible. In the approach used here for estimating the RAM data, advantage is taken of the fact that a statistically significant number of lasers are manufactured and tested for DUV lithography at Cymer. The failure data from these lasers are gathered, analyzed and corrected by the techniques described below.

In this paper, Cymer reports the first use of Failure Reporting Analysis and Corrective Action System (FRACAS) in determining the manufacturability, reliability and uptime performance of a laser optimized for DUV lithography. FRACAS is a state-of-the-art closed loop process to record, group and analyze failures and preventive maintenance actions. Software to measure the process is granted to Cymer by SEMATECH. It provides the required data for corrective action, highlights developing failure modes, and contributes data for statistical analysis. By far, the most important aspect of FRACAS is that it can be used to ensure closure of all problems.

The failures and preventive maintenance events of ELS-5000 lasers are captured by engineering, manufacturing and service personnel. The failures are grouped by problem, and problems are assigned owners who determine the Root Cause Solution (RCS). Problems are then retired only after the RCS has been determined effective by subsequent monitoring. As a result, the number of failure events decrease, resulting in improved manufacturability and reliability of the laser. As an example, in Figure 1 we show the failure rate per laser during the manufacture and test of these lasers, measured over 43 lasers, provided to us courtesy of Cymer Manufacturing.

Simultaneously, the key modules of the ELS-5000 laser are reliability tested separately, under stress and under typical operating conditions. Again, their failure mechanisms are analyzed for RCS.

Finally, a ELS-5000 laser is tested under typical stepper or scanner operating condition and its performance over a certain period recorded. This laser incorporates all the product corrections and improvements identified as solutions to the failures.

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According to SEMI E10-96, if reliability is improving (typical during early life of a product), then an overall RAM calculation is misleading. Instead a reliability growth model, such as the one developed by US Army Materials Systems Analysis Activity (AMSAA), must be used. However, in this case, by using FRACAS, Cymer rapidly converged to a stable product, and data from the tests performed on this laser may be analyzed via the techniques outlined in SEMI E10-96. An AMSAA model is not required to analyze the data.

In what follows, we describe the laser tests and the subsequent analysis to extract RAM data and the corresponding 80% confidence interval. Although a ELS-5000 laser was used for the study, the discussions are also valid for Cymer's EX-5000 laser which are optimized for scanners with catadioptic optics.

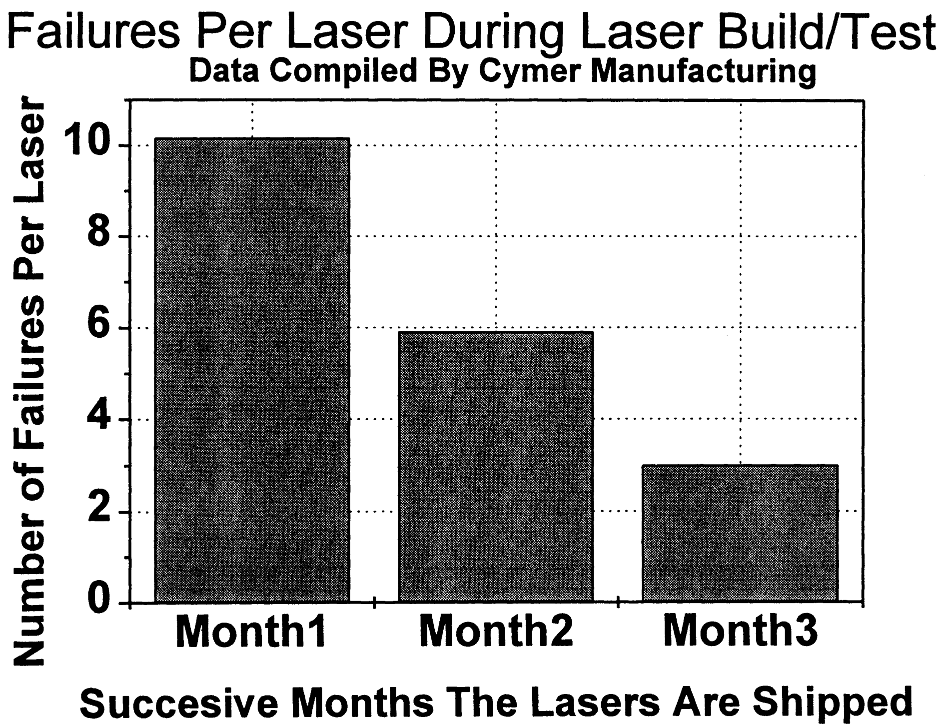


Figure 1. FRACAS ensures that the root causes for failure are identified and then tracked over time. This results in decrease in number of failures per laser.

Keywords: Deep-Ultra-Violet, Lithography, KrF, Excimer, Reliability, MPBF, MTBF, MTTR

2. LASER TESTS

The laser reliability tests started in December, '96 for a period of ten weeks. A representative ELS-5000 laser (Figure 2), built in late Month2, was used for these tests. The general specifications are listed below.

Laser Energy : 10mJ
Repetition Rate : 1000Hz
Spectral Width: <0.8pm at FWHM and <3.0pm at 95%
Maintenance:

- Gas Life: 100 million pulses or 5 days
- Diagnostics Check: Once a Week
- Laser Status Test and Report: Once a Week
- Laser windows inspection: 1000 million pulses, replace if required
- Laser Output Coupler inspection: 1000 million pulses, replace if required
- Laser Beam Splitter inspection: 1000 million pulses, replace if required

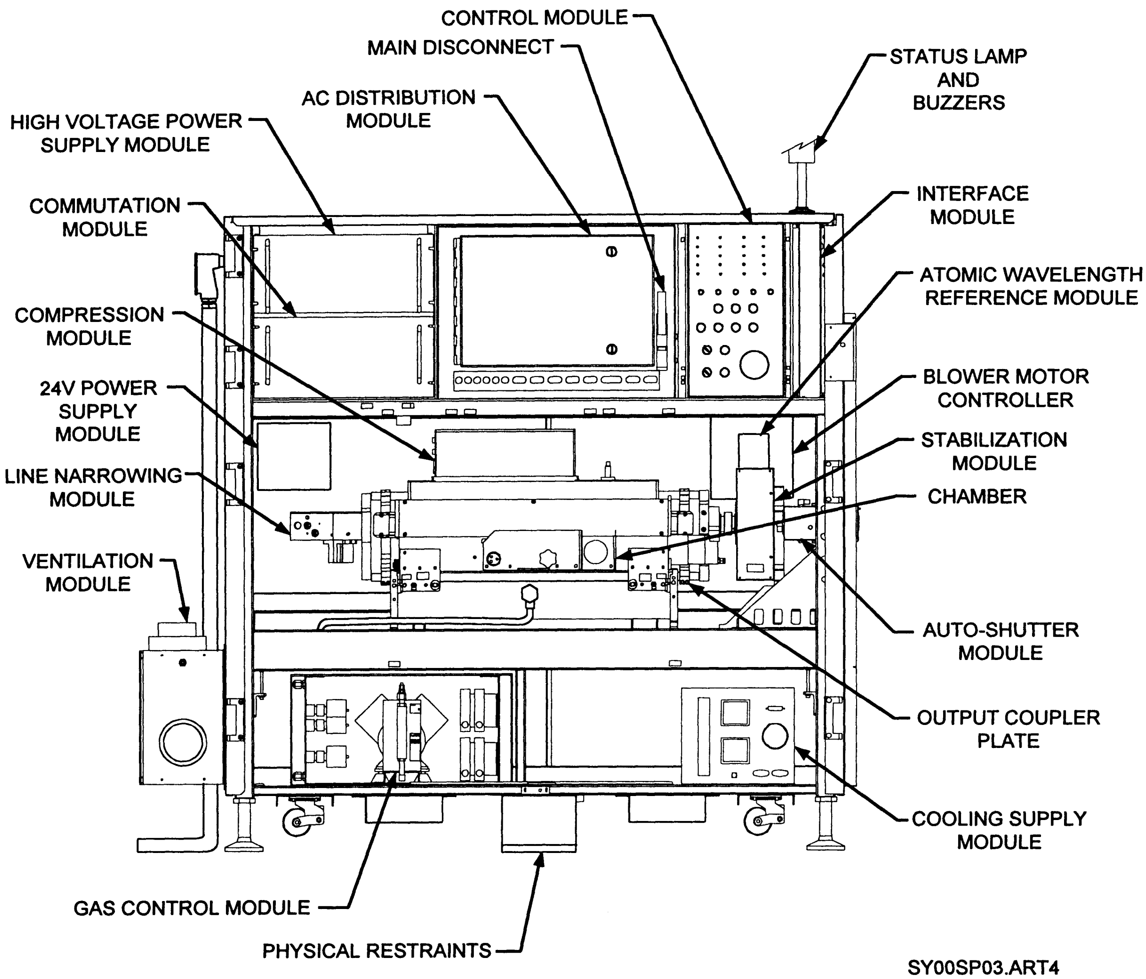


Figure 1. ELS-5000 with relevant modules.

The laser also has to meet a multitude of other specifications that depend on the stepper or scanner requirements. An optical diagnostics set-up, placed in front of the laser continuously monitored the laser specifications, and any out-of-specification was declared as an interrupt. The list of specifications that were measured are listed in Table 1.

Table 1 Laser Performance Parameter (and their impact on stepper/scanner) measured during tests.

Spectral Bandwidth and Spectral Energy Distribution	⇒ (affects)	Resolution, Depth of Focus
Relative Wavelength Stability	⇒	Focal Plan Stability (long term) Resolution, D.O.F., (Short Term)
Absolute Wavelength Stability	⇒	Magnification, Distortion
Output Power	⇒	Throughput
Repetition Rate	⇒	Energy Dose Accuracy, Speckle Reduction
Pulse-to-Pulse Energy Stability	⇒	Energy Dose Accuracy
Beam Profile, Beam Pointing & Beam Divergence Stability	⇒	Exposure Uniformity, Illuminator Efficiency
Polarization Stability	⇒	Illuminator Efficiency
Spatial Coherence	⇒	Speckle, Exposure

The diagnostics used to simulate stepper/scanner performance are shown in Figure 2. The laser was operated in a burst mode, similar to its operating mode in a stepper or scanner (Figure 3). However, to expedite the test, the laser was operated non-stop for 24 hours a day for ten weeks. The operating states of a typical semi-conductor capital equipment and that of the laser used in this test is shown in Figure 4.

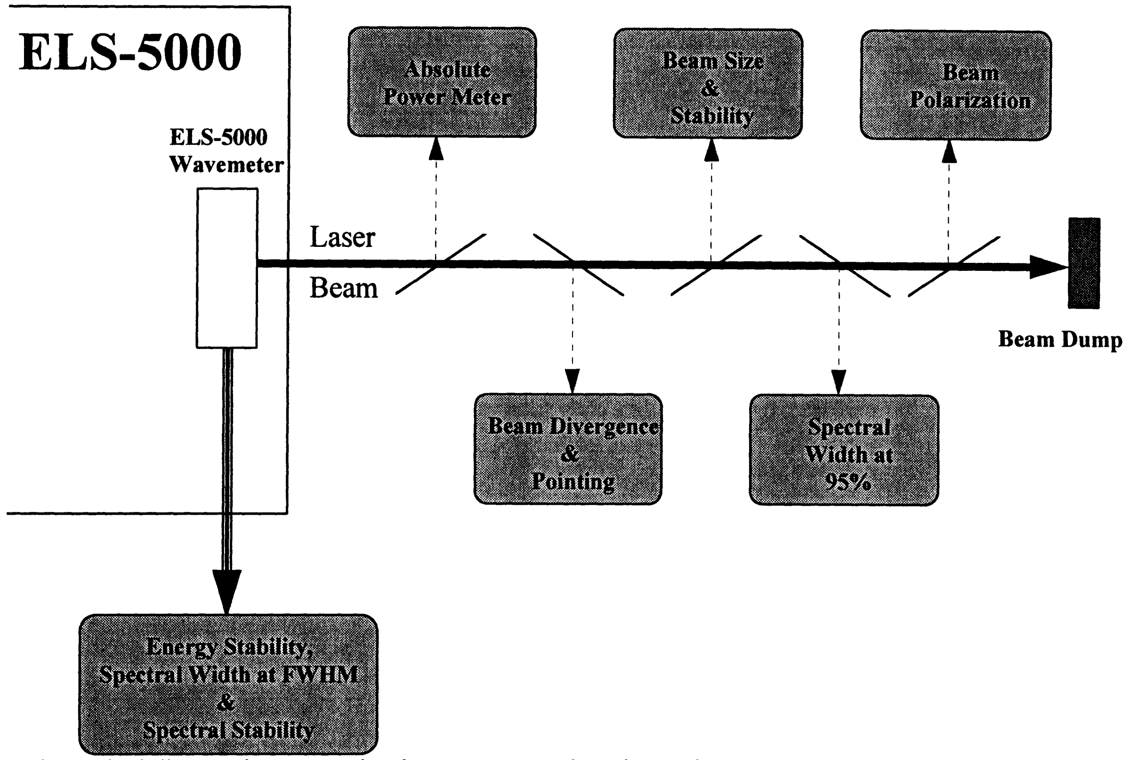


Figure 2. The optical diagnostics use to simulate a stepper. The relevant beam parameters were measured and any out-of-specification condition was considered as an interrupt.

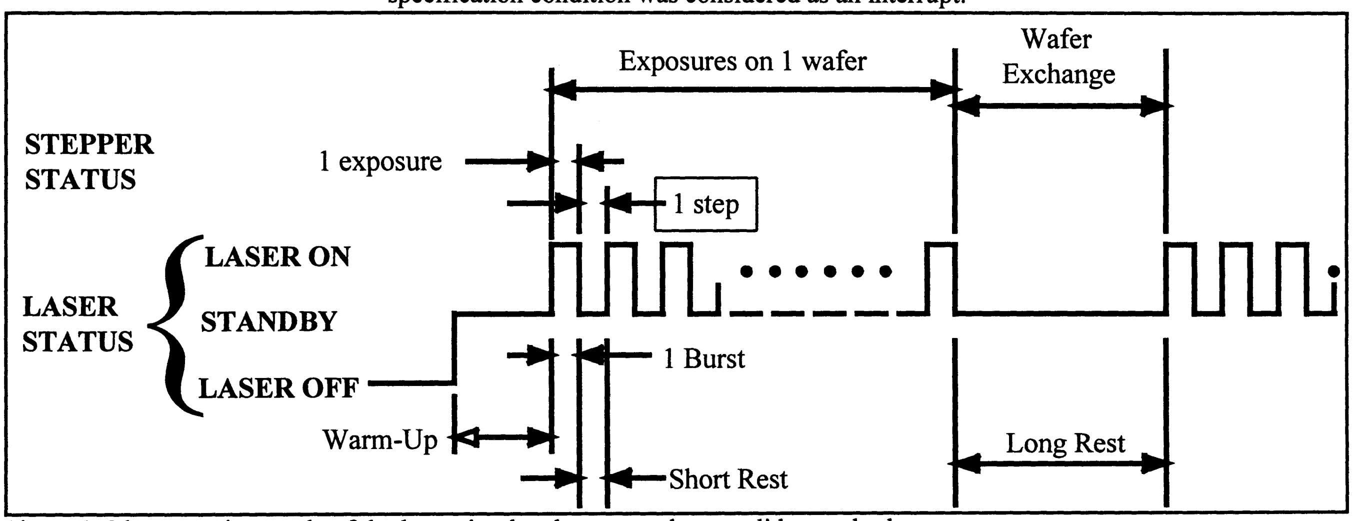
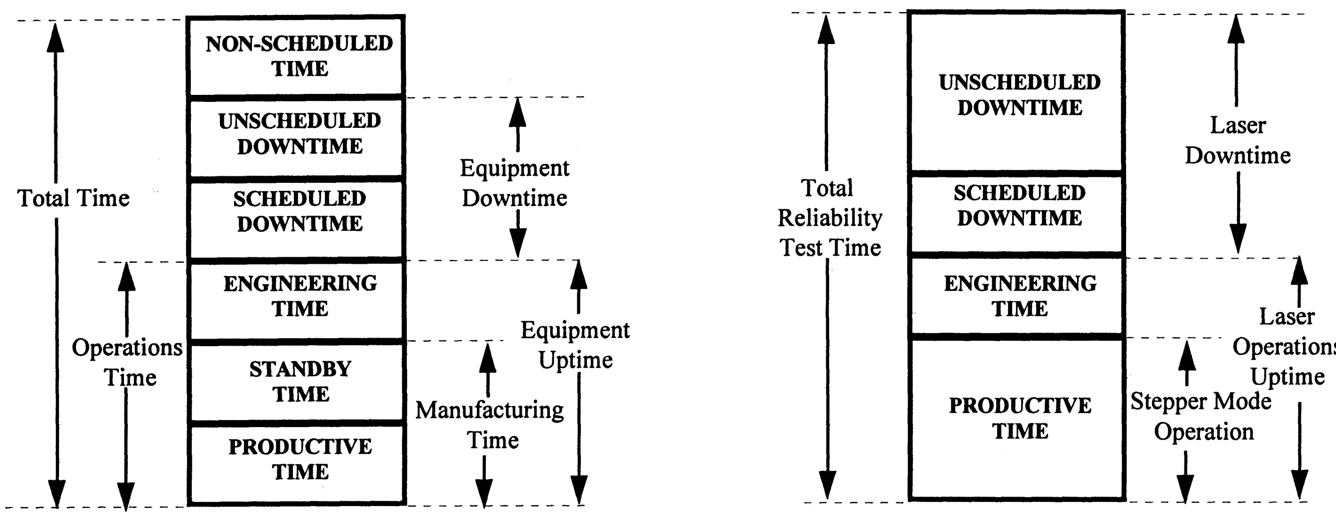


Figure 3. The operating mode of the laser simulated a step-and-repeat lithography laser.



Equipment States Stack Chart from SEMI E10-96 **ELS-5000 States During Reliability Test**

Figure 4. The states of ELS-5000 as compared to the states of a typical semi-conductor equipment

The results of the ten week operation are summarized below in Table 2.

Table 2.0 Summary of Test

Number of pulses during ten weeks = 2,900 million
Number of Gas Refills = 25 (~ 116 million pulses per fill)
Number of Interrupts (interrupt is sum of failures and assists) = 7
Number of failures = 5 (due to chamber, enclosure, gas module, Line Narrowing Package and Pulsed Power)
Number of modules or components replaced: 3 (1 chamber, two laser windows)
Total repair time = 13 hours

During the tests, the laser was maintained as per the specified maintenance intervals. In one or two cases, where the maintenance intervals were not known, experiments were conducted to determine such intervals. As an example, ELS-5000 is equipped with an Atomic Wavelength Reference (AWR) that ensures that the absolute accuracy of the laser wavelength. The wavemeter must be periodically calibrated, i.e. maintained. In order to determine the maintenance interval, the wavemeter was not calibrated, but permitted to drift. The AWR was used to measure the drift. Figure 5 shows the drift in the wavemeter, as measured over 1,000 million pulses. From the graph, we conclude that the periodic maintenance interval, to ensure an absolute accuracy of <0.1pm, is about 100 million pulses (or every gas refill). Figure 6 shows some of the critical spectral parameters, measured over the ten week period.

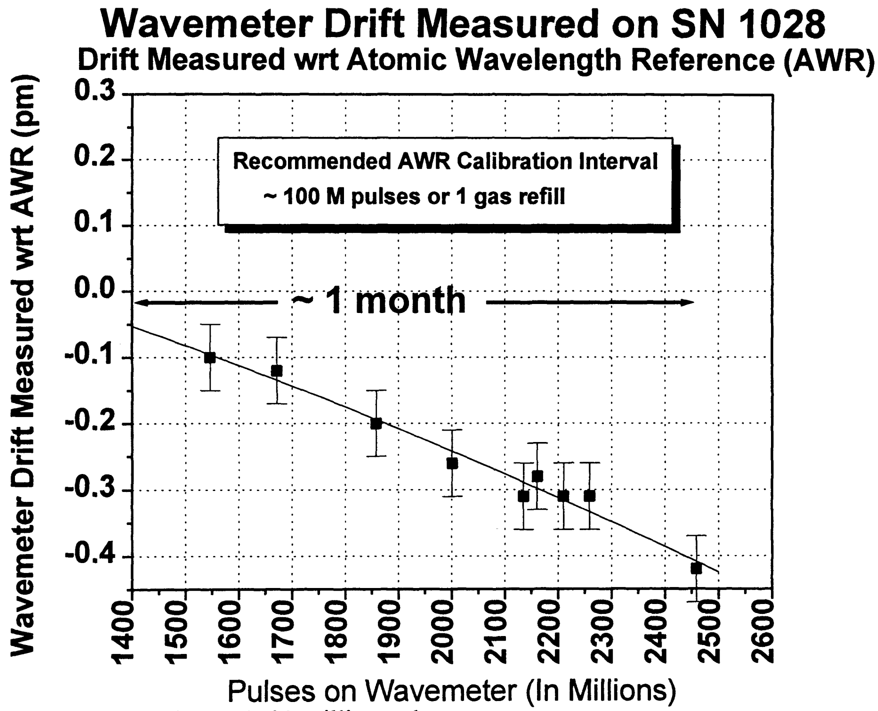


Figure 5. Drift in wavemeter measured over 1000 million pulses.

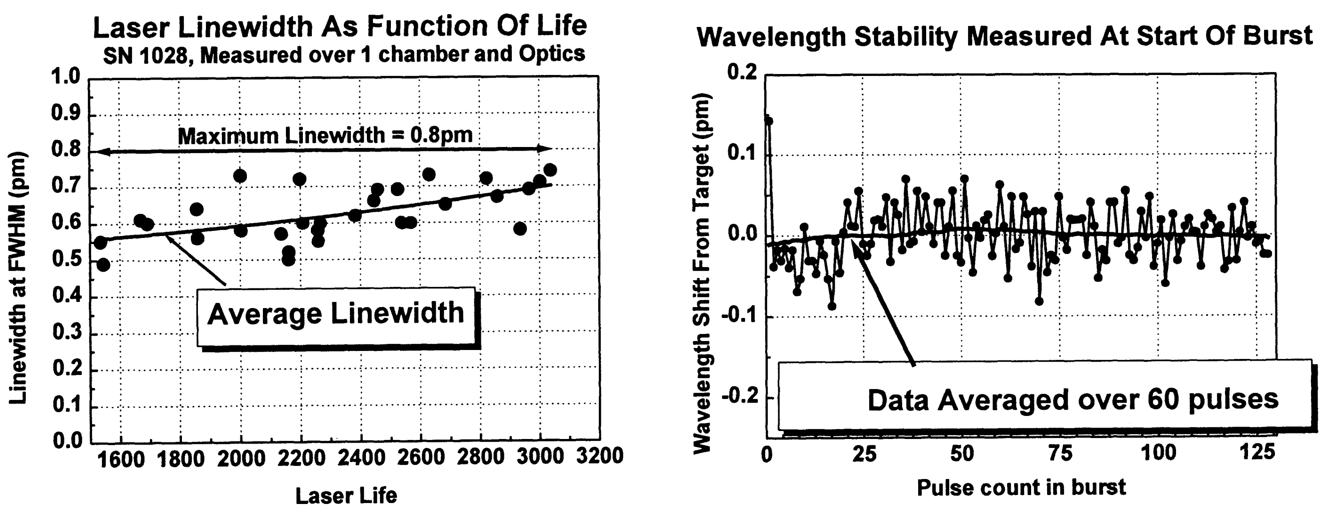


Figure 6. Spectral Data measured on the laser.

3. RAM ANALYSIS

Since the laser produces pulses of light, the appropriate independent variable for the analysis is pulses or (in the terminology used in SEMI E10-96) cycles. Therefore, the lasers Mean Pulses (Cycles) between failures (MPBF) is defined as the total number of pulses divided by the number of failures during those pulses. Thus,

$$\text{MPBF} = \frac{\text{Total Laser Pulses}}{\text{\# of Failures}}$$

The Mean time to repair (MTTR) is the average time it takes to correct a failure and return the laser to a condition where it can perform lithography. Therefore,

$$\text{MTTR} = \frac{\text{Total Repair Time}}{\text{\# of Failures}}$$

The laser's utilization can be measured by the laser's uptime, defined as

$$\text{Laser's Uptime (\%)} = \frac{\text{Laser's Operation Time - Unscheduled Downtime}}{\text{Laser's Operation Time}}$$

where non-relevant unscheduled downtimes have been removed from the data. A relevant downtime event is defined as an event that is a result of design or manufacture of the laser. Facilities related downtimes have been ignored.

From Table 2, we calculate the following for MPBF and MTTR.

MPBF ~ 580 million pulses
MTTR ~ 2.6 hours
The Laser's uptime is estimated to be greater than 99%.

The calculation of the lower and upper confidence limits of the MPBF utilizes the fact that a total of seven failures occurred during the ten week period. To estimate the lower and upper confidence limits, we have to multiply the estimated MPBF of 580 million pulses by factors specified in SEMI E10-96. A confidence level ranging from 80% to 95% are typical choices in the semi-conductor industry. A 90% lower limit factor from Table I in SEMI E10-96 (corresponding to seven failures) is 0.54. A 90% upper limit factor from Table II in SEMI E10-96 (corresponding to seven failures) is 2.0. Therefore, the 90% lower limit and upper limit on the MPBF is 313 million and 1160 million pulses. A 90% lower limit and a 90% upper limit combine to give an 80% confidence interval. The interval (313 million pulses to 1160 million pulses) is the 80% confidence interval for the laser's MPBF.

According to SEMI E10-96, confidence interval for MTTR is inappropriate.

The estimate of the usage rate of ELS-5000 in a manufacturing environment varies. In 1997, this is estimated to be between 3000 and 4000 million pulses. Assuming a 4000 million pulse use, a MPBF of 580 million pulses corresponds to a MTBF of about 1270 hours.

A critical assumption in this calculation is that the chip maker follows the maintenance schedule prescribed by Cymer. If such maintenance is not performed, the reliability of the laser is significantly affected and the RAM analysis performed here becomes meaningless. Often, the chip maker is ill-prepared to handle such maintenance because the usage rate of the laser varies significantly and is tied to the usage of the stepper and to the chip makers requirements. Since most of the maintenance intervals of the modules in the laser are based on pulse count, the chip maker is unable to predict when a maintenance should be performed. To minimize the unpredictability of the maintenance schedule, Cymer has developed software in ELS-5000 that forewarns the chip maker about an impending maintenance before the maintenance limit is reached. The software estimates the usage rate of the laser and calculates when a particular module would require maintenance. If the time to maintain the module is less than 100 hours, a warning is generated to prepare the chip maker for the impending maintenance of that module. This warning is expected to minimize occurrences of missed maintenance schedule.

4. CONCLUSION

The above calculations is our first estimate of the MPBF and MTBF of ELS-5000. We estimate that the MPBF and MTBF of the laser is 580 million pulses and 1270 hours. The laser's uptime is better than 99%. The use of FRACAS by Cymer engineering, manufacturing and field service resulted in a rapid maturity of the new ELS-5000 laser product. As the chip makers begin using the lasers, FRACAS will ensure identification and closure of problems observed by them to minimize their downtime.